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Energy performance of balanced heat recovery systems with load-balancing

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Abstract

The load-balancing method is to make the different amount of heating and cooling loads to be similar as possible for handling the more load by the balanced heat recovery (BHR) system which has higher energy performance than auxiliary system. When this method is applied, the zone set temperatures should be in comfort range and the additional energy to BHR system should not exceed the energy consumption by auxiliary system of general method. In result, the total energy consumption is lower, and some zones were more comfortable because heating or cooling set temperature was varied to the middle of comfort range.

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1. Introduction

It is conventional to provide heat using a boiler when heating and to extract heat using a chiller when cooling. The energy consumption for a boiler and a chiller is typically reduced by setting the temperature as low as possible for heating and as high as possible for cooling, within a thermal comfort range (e.g., 18°C for heating and 28°C for

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cooling). In this case, the ratio of people who feel comfortable is low because the set temperatures are at the edges of the thermal comfort range.

When the heating and cooling loads occur simultaneously, a balanced heat recovery (BHR) system could be applied. Such systems work year-round to recover all internal heat instead of adding external heat [1]. In other words, it is possible to cool the zones that need cooling by recovering internal heat, and to use it to heat the zones that need heating simultaneously. To recover the heat from returned chilled water from a cooling zone, refrigeration plant utilizing a water source (e.g., a water source heat pump) should be applied. Because it is able to simultaneously heat and cool, this system reduces energy consumption.

The efficiency of BHR systems is high when the heating and cooling loads are similar. When one load or the other is larger, the BHR system handles amounts of the heating and cooling loads based on smaller load, and then the remaining load is handled by auxiliary system (*general method*). Generally, the COP (Coefficient of Performance) of the water-source refrigeration plant of BHR system is higher than that of the auxiliary equipment (e.g., air-source chiller, boiler). Therefore, it is more efficient to handle the heating and cooling loads as much as possible by the BHR system in an acceptable temperature range. In other words, it is more efficient to balance the heating and cooling loads at higher levels for increasing the use of the BHR system and reducing auxiliary system's usage (*load-balancing method*). This load-balancing method could reduce the total energy consumption of the BHR system. In addition, it is possible to enhance comfort of heating or cooling zones because more heat is provided to the heating zone when the cooling load is larger, and more heat is extracted from the cooling zone when the heating load is larger.

The aim of this study was to investigate the energy reduction effect when a load-balancing method was applied to a BHR system. To achieve this aim, the concepts of BHR and load-balancing are proposed, then the energy consumption of BHR systems with *general method* and with *load-balancing method* are compared.

Nomenclature

COP	coefficient of performance (COP_C : for cooling, COP_H : for heating) (-)
E	energy consumption (E_C : for cooling, E_H : for heating, E_{C+H} : total) (J)
E_A	available energy ($E_{C,A}$: for cooling, $E_{H,A}$: for heating) (J)
E_{BHR}	energy consumption of the BHR system (J)
$E_{BHR.add}$	determined additional energy for BHR system based on $E_{C,BHR.add}$ and $E_{H,BHR.add}$ (J)
$E_{C,BHR.add}$	possible additional required cooling energy for BHR system (J)
$E_{H,BHR.add}$	possible additional required heating energy for BHR system (J)
$E_{C,Aux}$	energy consumption of the cooling auxiliary system (J)
$E_{H,Aux}$	energy consumption of the heating auxiliary system (J)
E_{Tot}	total energy consumption (J)
$Q_{C,Aux}$	cooling load handled by cooling auxiliary system (J)
$Q_{H,Aux}$	heating load handled by heating auxiliary system (J)
$Q_{C,BHR}$	cooling load handled by BHR system (J)
$Q_{H,BHR}$	heating load handled by BHR system (J)
$Q_{C,BHR.lim}$	limit cooling load handled by BHR system (J)
$Q_{H,BHR.lim}$	limit heating load handled by BHR system (J)
$Q_{C,BHR.add}$	additional cooling load handled by $E_{BHR.add}$ (J)
$Q_{H,BHR.add}$	additional heating load handled by $E_{BHR.add}$ (J)
$Q_{C.Tot}$	total cooling load (J)
$Q_{H.Tot}$	total heating load (J)
α	Ratio of COP_H and COP_C ($= -COP_H / COP_C$) (-)

2. Balanced Heat Recovery (BHR) system

The need for BHR system has been increased because of the occurrence of large complex buildings, mostly with simultaneous heating and cooling from various facilities. In the winter, heating is required while the internal heat gained from the operation of a variety of equipment increases the cooling. In summer, cooling load occurs when the ambient temperature is higher than the comfort temperature, but still requires domestic hot water for shower. Between summer and winter, some buildings demand heating in north zones and cooling in south zones [2]. Several studies with various system names like the “heat pump for simultaneous heating and cooling” or the “energy balancing system” have established the feasibility of such systems by comparing cooling and heating-load profiles [3,4], by simulation [2,5,6,7], and by experiment [8].

The heating or cooling load is handled by heat extraction or provision with the aid of thermal medium. Therefore, the thermal medium should be provided at a certain temperature with available energy (E_A). To perform heating or cooling continuously, a process to provide a thermal medium with E_A is required. To provide available energy for heating ($E_{H,A}$) or cooling ($E_{C,A}$), the heating energy (E_H) or the cooling energy (E_C) need to be consumed to returned hot or chilled water which does not contain $E_{H,A}$ or $E_{C,A}$ for recirculation.

To perform cooling and heating, in a conventional system, a boiler or a chiller is typically applied to make $E_{H,A}$ or $E_{C,A}$, and the energy consumption (E_{H+C}) is $E_H + E_C$ (Fig. 1a). In BHR system, the water-source refrigeration plant is applied to provide both heating and cooling as the plant can produce $E_{H,A}$ and $E_{C,A}$ simultaneously. If E_H and E_C are the same, the energy consumption of the BHR system (E_{BHR}) is not $E_H + E_C$ but equal to E_H or E_C (Fig. 1b). The heating load and cooling load handled by E_{BHR} of the BHR system ($Q_{H,BHR}(-), Q_{C,BHR}(+)$) have relation depending on the heating COP (COP_H) and cooling COP (COP_C) as eq. (1).

$$Q_{H,BHR} = \alpha Q_{C,BHR} \quad \left(\text{where, } \alpha = -\frac{COP_H}{COP_C} \right) \quad (1)$$

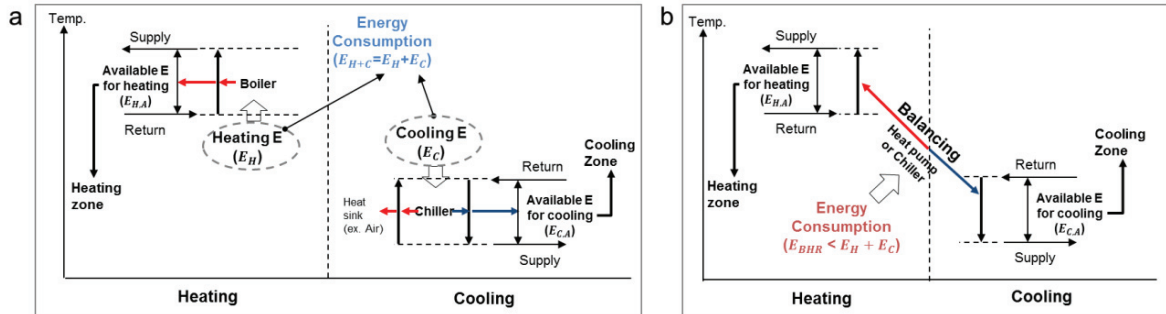


Fig. 1. Concept diagram: (a) Conventional system, (b) Balanced Head Recovery (BHR) system

3. General method vs. Load-balancing method

When BHR system is applied, there are two ways to reduce energy consumption: 1) reducing the heating and cooling loads or 2) increasing the efficiency. Of these two, the first is the *general method* to reduce the loads by setting room temperatures at the edges of the thermal comfort range. The second is the *load-balancing method* to increase the COP of whole system. The second approach is proposed as the subject of this study.

Fig. 2 shows the difference of load handling and comfort between general method and the load-balancing method when $Q_{H,Tot} < \alpha Q_{C,Tot}$, and detailed description will be described in chapters 3.1 and 3.2.

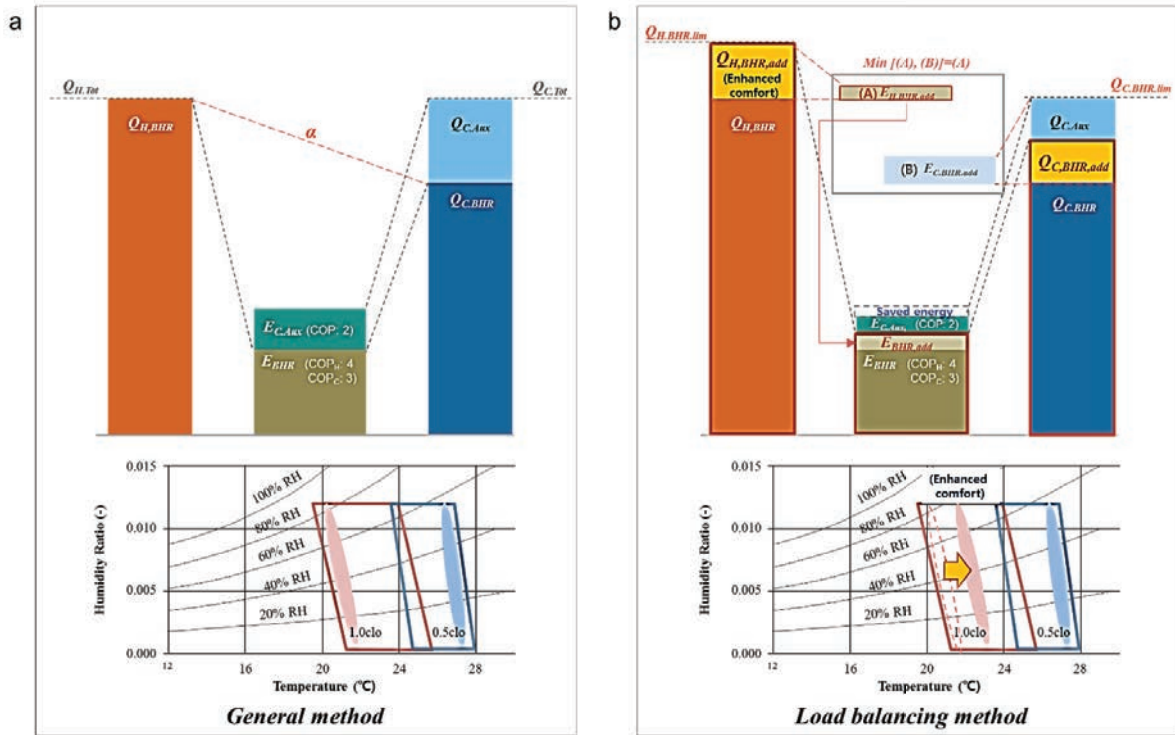


Fig. 2. Difference of load handling and comfort between (a) general method and the (b) load-balancing method (when $Q_{H.Tot} < \alpha Q_{C.Tot}$)

3.1. General method

In general, room temperatures are set as high as possible for cooling zones (e.g., 28°C) and as low as possible for heating zones (e.g., 18°C) to reduce the energy consumption. If the amount of total heating load ($Q_{H.Tot}$) and total cooling load considering α ($\alpha Q_{C.Tot}$) are the same with these set temperatures, all of loads could be handled by a BHR system. If the amount of $Q_{H.Tot}$ and $\alpha Q_{C.Tot}$ are different, the BHR system handles amounts of the cooling and heating loads based on smaller load and the remaining of the larger load is handled by auxiliary system.

In the BHR process (using BHR system), the energy consumption of the BHR system (E_{BHR}) is determined based on the relations of loads ($Q_{H.Tot} = \alpha Q_{C.Tot}$, $Q_{H.Tot} > \alpha Q_{C.Tot}$ or $Q_{H.Tot} < \alpha Q_{C.Tot}$), and then the loads handled by BHR system ($Q_{H.BHR}$, $Q_{C.BHR}$) are determined. In the auxiliary process (using auxiliary system), the remaining load to be handled by auxiliary system ($Q_{H.Aux}$, $Q_{C.Aux}$) is determined, and then the energy consumption of the auxiliary systems ($E_{H.Aux}$, $E_{C.Aux}$) are determined. The total energy consumption (E_{Tot}) is the sum of E_{BHR} , $E_{H.Aux}$ and $E_{C.Aux}$.

Fig. 2 shows the E_{BHR} and $E_{C.Aux}$ when $Q_{H.Tot} < \alpha Q_{C.Tot}$. Although the $Q_{H.Tot}$ and $Q_{C.Tot}$ are same, $Q_{H.BHR}$ and $Q_{C.BHR}$ are different because of α in eq. (1). Therefore, the amount of $Q_{C.BHR}$ could be handled by BHR system while the amount of $Q_{C.Aux}$ ($= Q_{C.Tot} - Q_{C.BHR}$) should be removed by auxiliary equipment.

3.2. Load-balancing method

To increase the COP of the whole system compared to when the general method is applied, it is required to maximize the usage of high efficiency equipment (BHR system) and minimize the usage of low efficiency equipment (Auxiliary system). When $Q_{H.Tot} \neq \alpha Q_{C.Tot}$, the usage of BHR system could be maximized and the usage

of auxiliary system minimized if $Q_{H.Tot}$ and $\alpha Q_{C.Tot}$ are balanced to be as similar as possible ($Q_{H.Tot} \approx \alpha Q_{C.Tot}$). In other words, if the load-balancing is performed, the energy consumption should be less as the BHR system has higher COP than auxiliary system in general.

When performing load-balancing, the heating load should be determined to allow a thermal comfort range (A) and the cooling load also should be determined allow a thermal comfort range (B), while consuming less energy than the general method is applied (C).

- (A) When the load-balancing method is applied, the set temperature for heating could be higher in the thermal comfort range (e.g., 22°C) to provide more cool by BHR when $Q_{H.Tot} < \alpha Q_{C.Tot}$. With this set temperature, the limit heating load handled by BHR system ($Q_{H.BHR.lim}$) is determined. However, the $Q_{H.BHR.lim}$ is equal to $Q_{H.BHR}$ when $Q_{H.Tot} = \alpha Q_{C.Tot}$ or $Q_{H.Tot} > \alpha Q_{C.Tot}$ because if $Q_{H.BHR.lim}$ is modified to make it more comfortable in these cases, the more energy usage should be occurred. Then, the possible additional required energy for BHR system ($E_{H.BHR.add}$) is determined based on the difference between $Q_{H.BHR}$ and $Q_{H.BHR.lim}$ (see eq. (2)).
- (B) When the load-balancing method is applied, the set temperature for cooling could be lower in the thermal comfort range (e.g., 24°C) to provide more heat by BHR when $Q_{H.Tot} > \alpha Q_{C.Tot}$. With this set temperature, the limit cooling load handled by BHR system ($Q_{C.BHR.lim}$) is determined. However, the $Q_{C.BHR.lim}$ is equal to $Q_{C.BHR}$ when $Q_{H.Tot} = \alpha Q_{C.Tot}$ or $Q_{H.Tot} < \alpha Q_{C.Tot}$ because if $Q_{C.BHR.lim}$ is modified to make it more comfortable in these cases, the more energy usage should be occurred. Then, the possible additional required energy for BHR system ($E_{C.BHR.add}$) is determined based on the difference between $Q_{C.BHR}$ and $Q_{C.BHR.lim}$ (see eq. (2)).
- (C) The additional energy consumption for (A) and (B) should not exceed the energy needed by the auxiliary system when the general method is applied ($E_{H.Aux}$, $E_{C.Aux}$). The COP of BHR system is higher than that of auxiliary system in general, so the $E_{H.Aux}$, $E_{C.Aux}$ are always larger than $E_{H.BHR.add}$ and $E_{C.BHR.add}$ respectively. Therefore, this criteria is not considerable.

Therefore, the determined additional energy for BHR system ($E_{BHR.add}$) is the minimum value among $E_{H.BHR.add}$ from (A) and $E_{C.BHR.add}$ from (B).

$$E_{BHR.add} = \text{Min}(E_{H.BHR.add}, E_{C.BHR.add}) \quad (2)$$

$$\text{where, } E_{H.BHR.add} = -\frac{Q_{H.BHR.lim} - Q_{H.BHR}}{COP_H} \text{ and } E_{C.BHR.add} = \frac{Q_{C.BHR.lim} - Q_{C.BHR}}{COP_C}$$

Fig. 2 shows effect of load-balancing method compared to the general method when $Q_{H.Tot} < \alpha Q_{C.Tot}$. The load-balancing method consumes more energy for BHR process as much as $E_{BHR.add}$ compared to the general method. However, the reduced energy for an auxiliary process is larger than $E_{BHR.add}$. As a result, the total energy consumption is smaller when the load-balancing method is applied. In addition, $Q_{H.BHR.add}$ was handled additionally in the heating zone, therefore, the thermal comfort of heating zone was also enhanced.

3.3. Comparative evaluation

Comparative evaluations of BHR systems with the general method (Case 1) and the load-balancing method (Case 2) were performed under static conditions for a second. Table 1 shows the input values for the simulation, and the results (also refer to Fig. 2).

The result shows that the energy consumption of the BHR system in Case 2 (672 J) is higher than in Case 1 (514 J), but that of the auxiliary system in Case 2 (363 J) is lower than in Case 1 (600 J). Therefore, the total energy consumption for Case 2 (1035 J) is lower than for Case 1 (1114 J). In addition, the room temperature of the heating zone was middle of thermal comfort range (22°C) for Case 2; therefore, thermal comfort of heating zone was also enhanced.

Table 1. Input values for the simulation and the results

Items		Heating zone	Cooling zone
Input	Zone	General	<ul style="list-style-type: none"> • Dimension: 10 x 10 x 4 m³ • Outdoor temperature: 5°C • Limit Temp.: 18°C (Case 1), 22°C (Case 2)
		Envelope	<ul style="list-style-type: none"> • Heat transmission coefficient: 0.254 W/m²K • Solar intensity: 139 W/m² • Transmittance: 0.5 • Window area: 40 m²
	Solar	Solar	<ul style="list-style-type: none"> • Window area: 0 m² • Air change per hour : 0.5
		Ventilation	<ul style="list-style-type: none"> • Air change per hour: 0.5 • Internal load: 3600 W
	Equipment	Internal	<ul style="list-style-type: none"> • Internal load: 0 W • 3 (Cooling by BHR system)
		BHR COP	<ul style="list-style-type: none"> • 4 (Heating by BHR system) • 2 (Cooling by auxiliary system)
	Auxiliary COP	Auxiliary COP	<ul style="list-style-type: none"> • 1 (Heating by auxiliary system) • 2 (Cooling by auxiliary system)
	Result	Handled load	<ul style="list-style-type: none"> Case 1 • $Q_{H,BHR} = -2055 \text{ J}$ Case 2 • $Q_{H,BHR} = -2688 \text{ J}$
		Energy Consumption	<ul style="list-style-type: none"> Case 1 • $E_{Tot} = E_{BHR} (514 \text{ J}) + E_{C,Aux} (600 \text{ J}) = \mathbf{1114 \text{ J}}$ Case 2 • $E_{Tot} = E_{BHR} (672 \text{ J}) + E_{C,Aux} (363 \text{ J}) = \mathbf{1035 \text{ J}}$
	Room temperature	Case 1	• 18°C
		Case 2	• 22°C

4. Conclusions

In this study, the potential for energy reduction was investigated when a load-balancing method was applied to a balanced heat recovery (BHR) system for a building with simultaneous loads. The conclusions were as follows:

- (1) The load-balancing method is increasing the loads handled by the BHR system which has higher COP than auxiliary system when the loads are different. This method considers the difference between heating and cooling loads handled by BHR system depending on the heating and cooling COP, and performs heating and cooling in a thermal comfort range while consuming less energy than when the load-balancing is not applied.
- (2) When the load-balancing method was applied, the total energy consumption was reduced, and the heating or cooling zones could be more comfortable because the temperature could be set in the middle of thermal comfort range. These findings could help building service designers and operators who deal with BHR systems.
- (3) The thermal comfort could be more considered in a range of not exceeding the auxiliary system energy consumption when general method is applied. This will be investigated as future study.

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